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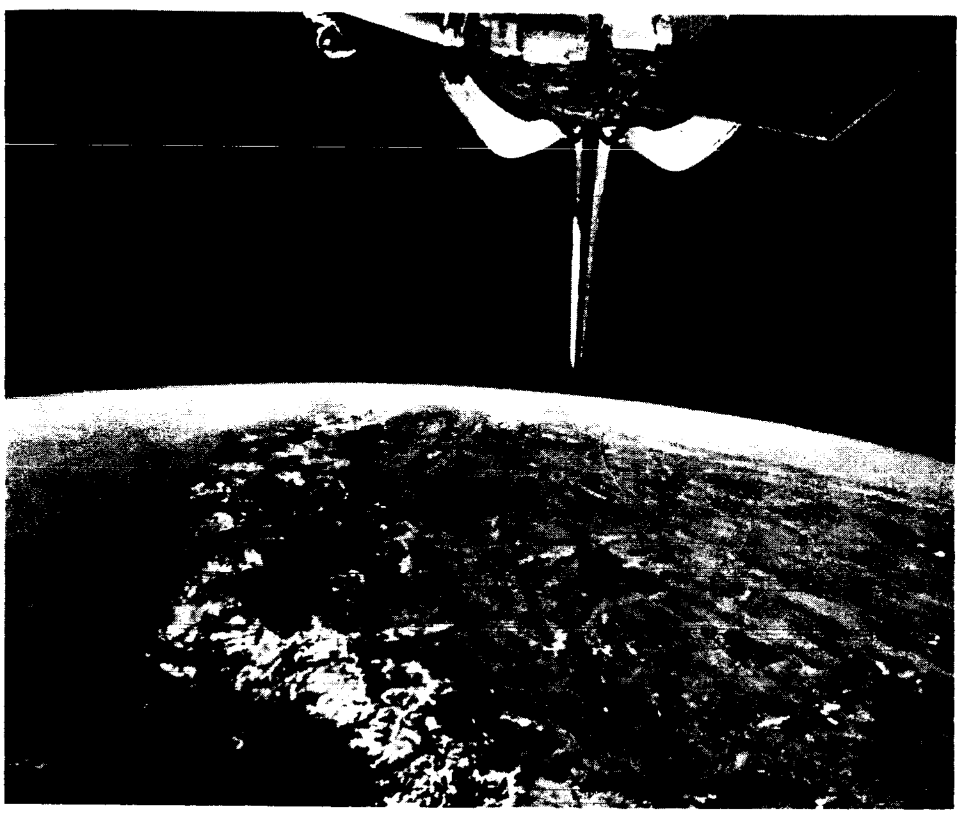
WORKSHOP ON

THE EARTH AS A PLANET



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WORKSHOP ON

THE EARTH AS A PLANET

Edited by
Lewis Ashwal, Kevin Burke, Maarten de Wit, and Gordon Wells

Sponsored by
The Lunar and Planetary Institute
Planetary Geology Division, Geological Society of America

Held in
Orlando, Florida
October 27, 1985

Lunar and Planetary Institute 3303 NASA Road 1 Houston, Texas 77058-4399

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Cover—*At an altitude of 360 kilometers, the Space Shuttle orbiter Challenger passes over the Great Himalayas and Tibetan Plateau during the STS-41G mission on October 6, 1984. In the upper right of the frame is the SIR-B antenna used to collect multiple-incidence-angle synthetic aperture radar imagery over 6.5 million square kilometers of the Earth's surface during the mission. Another important terrain-imaging experiment, the Large Format Camera, is contained in the cylinder at the rear of the payload bay. LFC photographs of the Tibetan Plateau have proved particularly valuable in resolving the tectonic mechanism by which Eurasia accommodates the collision with India.*

Contents

Introduction

Late in 1984 the Director of the Lunar and Planetary Institute and officers of the Planetary Geology section of the Geological Society of America met and developed the idea of convening joint workshops occasionally in association with the Annual Meeting of the Geological Society. This idea met with enthusiastic support at NASA Headquarters.

The first such workshop was held in Orlando, Florida on the Sunday before the 1985 Annual General Meeting of the Society and was devoted to the concept of "The Earth as a Planet." The twelve talks whose abstracts appear in this volume were presented (at short notice Don Anderson very kindly presented both his own talk and that of Alan Zindler and Stan Hart) and there was much stimulating discussion among the 66 people who attended. A summary of the afternoon session was prepared by Gorden Wells and that of the morning session was prepared by Kevin Burke.

The growth of NASA's recognition of the status of the Earth as a planet has been similarly fast and is nowhere more clear than in plans for the Earth observing system as a part of the Space Station (1) and in the work of the presently active Earth System Science Committee of the NASA Advisory Council (2). A good assessment of how space-based Earth science should develop on a shorter time scale can be found in the Report of the Research Briefing Panel on Remote Sensing of the Earth prepared in 1985 for the Presidential Space Advisor (3). These three reports together serve as a short introduction to the current range of scholarly and social planning in this important field.

References

(1) Earth Observing System: Working Group Report, NASA TM-86129 (published in August, 1984), NASA/Goddard Space Flight Center.
(2) Earth System Science: Overview 1986 (in press), NASA Headquarters, Washington, DC.
(3) Report of the Research Briefing Panel on Remote Sensing of the Earth, reprinted from Research Briefing, 1985, National Academic Press, Washington, DC. 17 pp.

Program

8:30

Kevin Burke (Lunar and Planetary Institute)
Welcome and Introduction

H. H. Schmitt (Consultant)
Earth-Moon Reflections

9:00-10:20

Mantle

Alan Zindler (Lamont Doherty Observatory)
The Mantle: Chemical Geodynamics

Don Anderson (California Institute of Technology)
The Mantle: Seismic and Geochemical Constraints

Brad Hager (California Institute of Technology)
The Mantle: Potential Field Considerations

10:20-12:00

Early Earth

Karl Turekian (Yale University)
Planetary Degassing Based on Ar Isotope Systematics

Frank Richter (University of Chicago)
Thermal Evolution

Maarten de Wit (University Witwatersrand/LPI)
What the Oldest Rocks Say

Discussion

1:30-3:30

Remote Sensing

Raymond Arvidson (Washington University)
Addressing Fundamental Geological Questions with Remote Sensing

John Ford (Jet Propulsion Laboratory)
New Perspectives (Radar Imaging)

Alexander F. H. Goetz (University of Colorado)
New Perspectives (Imaging Spectrometry)

Anne Kahle (Jet Propulsion Laboratory)
New Perspectives (Imaging Spectrometry in the Thermal Infrared)

Peter Mouginis-Mark (NASA Headquarters)
NASA Programs in Geology

3:40-4:50

Megageomorphology

Gordon Wells (NASA Johnson Space Center)
Megageomorphology: A New Orbital Perspective

John Everett (Earth Satellite Corporation)
Geomorphology from Space: A Global Overview of Regional Landforms

Workshop Summary

The Mantle: The Largest Part of the Earth

Presentations at the Orlando workshop that were linked by the theme of the Earth's mantle not only covered the range of sources of information about that huge volume of rock, but also benefited from the variety of independent (perhaps idiosyncratic?) scholarly approaches of those who made presentations.

What we know about the mantle comes from geophysical (gravity, seismology) and geochemical (petrology, isotope geochemistry) observations. One thing that soon became clear at Orlando was that no participant thought that either kind of information could be used on its own and, as Don Anderson strongly emphasized, the distinction between data derived by one technique or another is inappropriate in addressing the whole Earth. We have to consider *all* data. As a contribution to this end, Don concentrated on geochemical and isotopic data from mantle-derived igneous rocks. Alan Zindler and Stan Hart used data from the same source and it is perhaps significant that the two talks reached rather different conclusions on the structure of the shallow mantle and on the distribution of mantle reservoirs.

Karl Turekian discussed degassing of the Earth. His discussion concentrated on ^{40}Ar, a product of radiogenic decay that sheds light on the longer term evolution of the atmosphere. Frank Richter spoke on the thermal history of the Earth, emphasizing that the difference between modern ideas of thermal history and the ideas of Lord Kelvin depended at least as much on the fact that we use convection in our models as on the present-day recognition of radioactivity. Brad Hager discussed mantle physics. He outlined how recent seismic tomography results can be integrated with dynamic models of the geoid to improve understanding of mantle dynamics.

The Old Continental Crust of the Earth

Maarten de Wit chose to review what we can learn about the Archean continents from the well-exposed and intensely studied South African Kaapvaal craton. This ancient continental area has much to teach us and has become a new focus of interest with the developing idea that the diamonds brought up in its kimberlites are themselves very ancient.

The Moon

Jack Schmidt, the only GSA member to have set foot on the Moon, reminded us of what we can continue to learn about the Earth by thinking about lunar properties. In discussion, he showed no great enthusiasm for the currently popular idea that the Moon formed as a result of the impact of a Mars-sized object on the Earth.

New Perspectives on Terrestrial Remote Sensing

Having spent the morning exploring the creation of the Earth, the dynamics of the mantle, and the evolution of the crust through the mid-Archean, the workshop participants next turned their attention to recent innovations in the imaging of the Earth's surface by various remote-sensing techniques. Kevin Burke opened the afternoon session with reflections on the task at hand in promoting the goals of geological research within a national community of remote-sensing advocates dominated by oceanographic and atmospheric scientists. His experience in formalizing these goals in discussions with the Earth Systems Science Committee leads him to caution geologists on their expectations for new data from the polar-orbiting platforms of the future Space Station. The orbital characteristics of these platforms are likely to be dictated by the needs of meteorological and oceanographic research, which require daily observations under similar conditions. The instruments of prime importance to geologists, namely the Synthetic Aperture Radar and High Resolution Imaging Spectrometer, place by far the greatest demands upon the rate of data transmission from the platforms. Under these pressures, geologists should prepare to defend vigorously their research objectives that rely upon these remote-sensing instruments, or they risk compromises to the collection of data that best serves their interests.

Ray Arvidson amplified Burke's concerns with a demonstration of the NASA budgetary structure for future remote-sensing initiatives. The effectiveness of the atmospheric and oceanographic research lobby is easily apparent in the number of new starts for their instrumentation and the level of funding afforded to programs addressing their research agenda. The geological community would do well to reach a consensus on the types of remote-sensing data most needed because the success of their atmospheric and oceanographic counterparts as well as that of planetary scientists can be attributed to the ability to agree upon research and instrumentation priorities and to speak with a unified voice.

An update on the view from within NASA Headquarters was provided by Peter Mouginis-Mark, Acting Geology Program Manager. In addition to outlining the program status of the wide variety of airborne and spaceborne remote-sensing instruments of concern to geologists, he emphasized the need to pursue research topics complementary to the goals of the broad Earth science community. One such line of investigations, also mentioned by Burke and Arvidson, is the exploration of the global climatic record preserved by Quaternary deposits that can provide valuable guideposts for the study of future climatic change triggered by the natural and anthropogenic agencies of interest to the ocean and atmosphere modelers. Mouginis-Mark stressed the development and use of both experimental imaging spectrometers and conventional photographic systems, such as the Large Format Camera. Though funds are limited, there exists a definite need to begin preparing the geological establishment for the use of the new kinds of data that will become available from the Space Station polar platforms. One question raised by those impressed by Anne Kahle's presentation of the recent results from the airborne thermal infrared imaging spectrometer program was the possibility of an orbital experiment with that sensor aboard the Space Shuttle. Though it is not presently funded as an STS payload, Mouginis-Mark left open the possibility for pursuing an orbital test of the thermal infrared imaging system.

The evolution of orbital synthetic aperture radars was presented by John Ford with many illustrations of geological applications. The phased development of these imaging radar systems began with the L-band, fixed-look angle Seasat freeflyer and SIR-A payload carried by STS-2. A multilook angle system was incorporated by SIR-B during the STS-41G mission. Future Space Shuttle experiments will test multifrequency and multipolarization radars. The culmination of the SIR experiment series will be a multilook angle, multifrequency, multipolarization synthetic aperture radar operated from a polar-orbiting platform of the Space Station.

The development of remote-sensing techniques marking the transition from lithologic discrimination to actual identification of the mineral constituents of differing lithologies was addressed by Alex Goetz in his presentation on imaging spectroscopy. While the broad spectral bands of the Landsat Thematic Mapper allow the rough plotting of seven points about the diagnostic spectral curve of a selected mineral, the experimental Airborne Imaging Spectrometer specified 128 points between 1.2–2.4 micrometers. During the next few years, advances in airborne and orbital imaging spectrometers promise to generate 0.4–2.4 micrometer spectral curves of 196 to 224 discrete data points for each 30-meter pixel across a swath width of 12 to 50 kilometers. The dominant mineralogical composition of each ground cell could in theory be fingerprinted by matching the spectral plots with those obtained from mineral samples examined in the laboratory. A major subject of curiosity among the audience was the parallel development of computer processing techniques required to manipulate the massive amounts of spectral data to be returned from the planned High Resolution Imaging Spectrometer aboard a Space Station polar platform. Goetz foresees little difficulty in meeting the data processing demands given the current pace of technological breakthroughs in that field.

Having just returned from an aerial circumnavigation of Australia with the airborne Thermal Infrared Multispectral Scanner, Anne Kahle demonstrated results broadly comparable to those obtained by the Airborne Imaging Spectrometer for lithologic identification. Thermal inertia measurements derived from coordinated day and night images allow the determination of the relative density and heat capacity of adjacent rock units. One question posed from the audience asked whether this capability permits mineral identification in those cases where a thin weathering crust masks the mineralogy of rocks. Kahle replied that the technique offered that possibility only for rocks with weathering crusts less than 50 micrometers thick.

The focus of the afternoon session turned from instrument development to geological application, as Gordon Wells presented two case studies of the use of orbital imagery for megageomorphological investigations involving Eurasian tectonics and the genesis of longitudinal sand dunes. Of special interest to those asking questions was a reconstruction of global circulation during the waning stages of the last ice age. The evidence for his reconstruction came from radiocarbon-dated eolian deposits with airflow trajectories traced from sand dune orientations recorded by orbital remote-sensing systems. Wells stressed the need to create orbital imaging techniques responding to direct control during data acquisition by human observers in order to image active geomorphological processes, such as volcanic eruptions, floods, and dust storms.

The workshop concluded with a presentation by John Everett, who was standing in for Nick Short. Everett showed many examples of terrain features, including folded ranges, volcanic landforms, and river deltas, selected from the global inventory of Landsat imagery. The existing collection of Landsat images enables geologists for the first time to perform comprehensive morphological analyses of all terrestrial landforms. A compilation of global terrain types will be contained in a forthcoming NASA publication, *Geomorphology from Space: A Global Overview of Regional Landforms*, edited by Nick Short.

ABSTRACTS

GEOPHYSICAL AND GEOCHEMICAL CONSTRAINTS ON GLOBAL PROCESSES,

Don L. Anderson, California Institute of Technology, Pasadena, CA 91125

Individual Earth scientists have traditionally treated the Earth piecemeal utilizing techniques from a few disciplines. As new information is gathered the prevailing theories are modified to fit, but the basic assumptions are seldom reconsidered. One typical example is drawn from petrology. The bulk of the mantle is usually assumed to have its original composition in spite of the evidence that large scale differentiation occurred during and after accretion. Basalts are treated as original melts from primitive (pyrolite) material or from a "depleted low velocity zone" but always from an olivine-rich peridotite parent and usually from a mantle that is homogeneous in major elements. By combining planetary petrological, geochemical and geophysical data we derive quite a different model, which satisfies a large amount of diverse data but violates some standard terrestrial assumptions.

The planetary exploration program represents a contrasting approach to the study of a planet. New discoveries do not have to be dovetailed into existing theories and fresh insights have been gained on how a planet operates. Generally, a large amount of interdisciplinary information is obtained and the data itself, rather than preconceptions, controls the conclusions. The behavior of the other planets appears paradoxical when viewed from the standard terrestrial perspective. It is not the basic data but the terrestrial prejudices (the "paradigm") that give rise to these paradoxes.

Some terrestrial datasets are being integrated to obtain self-consistent views of ways the Earth operates. Global views from NASA missions are the current and projected lifeblood of some branches of Earth sciences such as oceanography and meteorology. The solid Earth sciences have been neglected by NASA. The rapid advances being made in astromony, planetary science and the fluid Earth sciences can be largely attributed to the technical and financial support available to these disciplines from NASA.

There has been some feedback into solid Earth sciences from NASA programs. The Apollo program upgraded geochemistry and petrology in this country and abroad. Landsat and Seasat provided extremely useful datasets. The short wavelength magnetic field of the Earth is now better understood.

The prospects for the future, however, are bleak unless the geological community gets behind the proposed Research Mission to Planet Earth, an integrated and systematic study of our planet with both space and ground based elements. Elements of the proposed mission include systematic mapping of the surface, including high-resolution, stereo, multispectral and radar techniques, mapping the gravity and magnetic fields, monitoring crustal deformation and imaging the interior of the Earth. Both international and interagency cooperation is required.

ADDRESSING FUNDAMENTAL GEOLOGICAL QUESTIONS WITH REMOTE SENSING;
Raymond E. Arvidson, Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130

Development of remote sensing techniques and methodologies are activities that are crucial precursors to being able to fully exploit observations of the earth from airborne and spaceborne platforms. Of equal importance is the development of a broad vision for the appropriate uses of remote sensing in addressing important scientific questions. Appropriate roles for remote sensing in the geological sciences have been considered recently by the Space Science Board of the National Academy of Sciences (National Academy, 1983), by NASA's Task Force on Scientific Uses of the Space Station (Banks et al., 1985), NASA's Earth Observing System (Eos) Science Working Group (NASA, 1984; Arvidson et al., 1985), and by NASA's Earth Systems Science Committee (Burke et al., in preparation). In each case, emphases have been placed on understanding the geological evolution of the Earth's continents over a variety of timescales and the roles of remote sensing in increasing that understanding.

Figure One illustrates schematically how exogenic and endogenic processes operate to produce the types and distribution of landforms, rock types, and debris exposed at the Earth's surface. Remote sensing observations can contribute fundamental information on the chemistry, mineralogy, physical properties, and morphology of continental surface areas, in addition to directly monitoring those processes (e.g., desertification, volcanic eruptions, floods) that occur over timescales consistent with the repeat period for coverage from either airborne or spaceborne platforms. Remote sensing data, combined with vigorous field, laboratory, and theoretical studies will undoubtedly tell us a great deal about the global-scale tectonic evolution of the continents and the Pliocene to Pleistocene climatic history of the Earth.

The NASA Earth Observing System (Eos) of the 1990s as presently envisioned will consist in part of a complement of Earthward-looking remote sensing instruments mounted on polar platforms. An initial Eos could consist of a platform with, among other instruments, an imaging spectrometer that is a follow-on to JPL's planned sequence of AIS, AVIRIS, and SISEX instruments (Goetz et al., NASA Imaging Spectrometer Science Advisory Group Report, in preparation). A thermal mapping spectrometer and a multifrequency, polarization, and look angle radar imager are also planned for Eos. The daily data return from Eos could be in the terabyte range.

Data to be obtained from an Eos or from other polar platforms that fly as part of the Space Station will offer unprecedented opportunities to derive information on a global basis that is pertinent to the tectonic evolution of the continents and to those aspects of Earth's climatic history that can be unraveled through synoptic observations of the Earth's surface. We do, however, have a great deal to accomplish to be ready to utilize Eos-style data. We need to continue to develop techniques and methodologies. We also need to learn, through experience, how to utilize remote sensing data, combined with other sources of information, to most efficiently and appropriately address global scale questions such as the tectonic and climatic histories that are recorded in the chemical, mineralogical, and physical properties of the Earth's surface.

REFERENCES CITED

Arvidson, R.E., D. Butler, R.E. Hartle, Eos--The Earth Observing System of the 1990's, Proceed. IEEE, V.73, 1025-1030, 1985.

Banks, P. and others, SESAC Task Force on Scientific Uses of the Space Station: Summer Study Project, NASA Doc., 117 p., 1985.

NASA, "Earth Observing System--Science and Mission Requirements," Working Group Rep., vol.1, NASA TM-86129, 58 p., 1984.

National Academy Sciences, A Strategy for Earth Science from Space in the 1980's: Part 1--Solid Earth and Oceans, National Academy Press, 99 p., 1982.

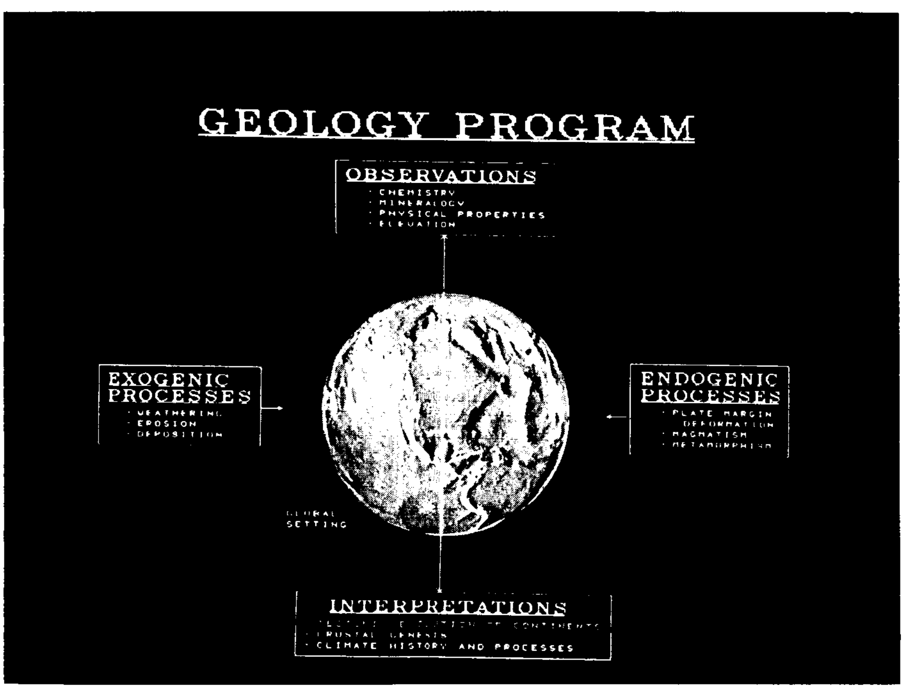


Figure One - Schematic view of processes that operate on or near the Earth's continental surface, observations that can be obtained via remote sensing techniques, and interpretations that touch on important scientific questions.

WHAT THE OLDEST ROCKS SAY. Maarten de Wit, BPI Geophysics, University of the Witwatersrand, Johannesburg, and Lunar and Planetary Institute, 3303 NASA Road One, Houston, Texas 77058

(1) MID ARCHEAN CONTINENTAL CRUST-LITHOSPHERE

Five composite geological sections through the Mid-Archean (3.0-3.8 Ga) crust of the Southern African craton show that by 3.0 Ga, continents in excess of $5x10^5$ km^2 had crustal thicknesses of at least 30-40 km with geotherms comparable to those of today, and contained at least one major deep seismic reflector (Fig. 1). Old diamonds (3.2-3.3 Ga) derived from below this crust dictate that it was at least partially underlain by a subcontinental lithosphere of 70-170 km thick. Rocks from sedimentary basins formed on top of this lithosphere between 3.5 and 2.7 Ga, provide ample evidence for the presence of rift, trench-forearc and foreland basins similar to those seen within and around todays continents. Tectonic juxtaposition of two geologically different granulite terrains within this craton and their combined uplift before 2.7 Ga (Sections I and II, Fig. 1) is best explained by continental thickening due to major plate collision. It thus seems likely that the mechanics of continental tectonic processes were the same in the Mid-Archean as they are today. The distribution of rocks on a recently compiled geologic map of Gondwana suggest that at least 80% of the southern continents existed by the end of the Archean (2.5 Ga) and more than 90% by 2.0 Ga, assuming surface distributions extend through the crust. In concert, the above geologic facts are consistent with a continental growth model approaching that of Armstrong (1968, 1981; Fig. 2).

(2) MID ARCHEAN OCEANIC CRUST-LITHOSPHERE

New field observations and a structurally restored geologic section through the 3.5-3.6 Ga Barberton greenstone belt shows that it's mafic to ultramafic rocks form a pseudostratigraphy comparable to that of Phanerozoic ophiolites (de Wit et al., 1985). It consists of an intrusive-extrusive mafic-ultramafic section, underlain by a high-temperature tectono-metamorphic residual peridotitic base, and is capped by a chert-shale sequence which it locally intrudes. Geochemical data support an ophiolitic comparison (Fig. 3). Fractionation of high temperature melting PGE's ($>2500^oC$) in the residual rocks suggest a lower mantle origin for the precursors this crust (Fig. 4; Tredoux et al., 1985). An oceanic rather than arc-related crustal section can be inferred from the absence of contemporaneous andesites. This ancient simatic crust was thin (< 3 km), contains a large ultramafic component ($\simeq$ 25%), is pervasively hydrated (> 95%) with H_2O contents ranging between 2-15% and consequently has a low density ($\simeq 2.67$ g/cm^3; Figs. 5 and 6); it is also chemically severely altered. Pillow structures and geochemistry reveal that this alteration occured during interaction with hydrous fluids during crust formation. A chemical lithosphere between 5-15 km is calculated for 45-20% partial melting, respectively. The above observations are in agreement with models predicting a higher oceanic Archean heat flux than today, associated with deep mantle diapiric upflow.

Integrated, the rock record appears compatable either with a model 3.0-3.5 Ga earth covered by many (25-several hundreds) small plates incorporating thick continental fragments (like icebergs; c.f. Pollack and Sprague, 1981), or a model which infers a more efficient fission-fussion of supercontinents by means of microplate fragmentation (like ice-shelf calving), than seen in the

Phanerozoic. The 3.5 Ga earth had a magnetic field (hence a core) comparable to that of today, but probably not yet a 2-layer mantle.

The sudden onset of preservation of the granitoid rock record around 3.8 Ga is probably related to the initial hydration of simatic crust, since without such alterations, the formation of granitoids is extremely inefficient (Campbell and Taylor, 1983). The recycling process of low density Archean simatic crust (2/67 g/cm^3), and/or lithosphere (about 3.0 g/cm^3) would have been resisted: obduction ruled. Conversely, the earliest continental nuclei may have originated through rapid (at an average Archean half spreading-rate) intraoceanic obduction, the continuous stacking and subsidence of such hydrated simatic thrust piles, and their inevitable one-stage melting to yield trondhjemite-tonalite segregates under varied P, T, H_2O conditions at depths greater than 20 km during overthrusting (Fig. 7). This model closely approaches that of McGregor (1979) and Barker et al. (1981). Globally these bimodal nuclei formed over an extended period of time (between at least 3.8-3.0); together with their depleted dunitic-harzburgitic keels they provided platforms (tectospheres, c.f. Jordan, 1981) for further plate tectonic accretion and collision. Prior to this scenario the average MOR stood above sea level; consequently "dry recycling" of earth lithosphere prevailed. Comparative studies of other planets and satellites such as Mars or Io may reveal more about the geodynamics of planet earth before the "sudden" drowning of spreading centers, and may provide more realistic working hypothesis for geologists to pursue in the field.

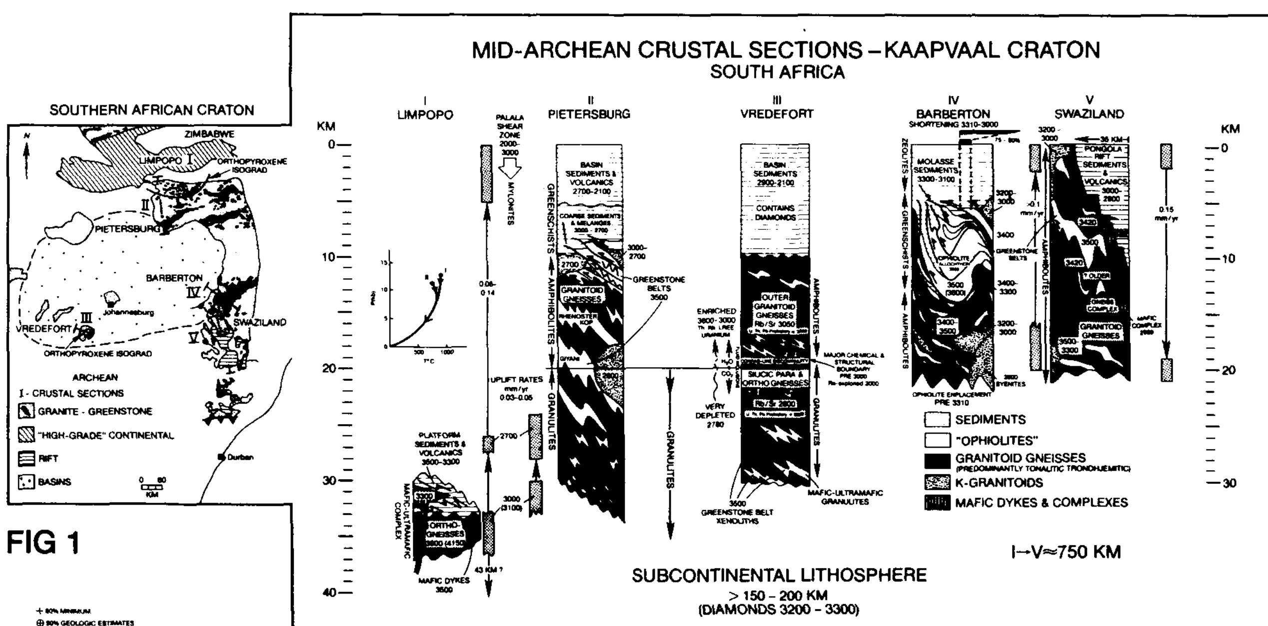


FIG 1

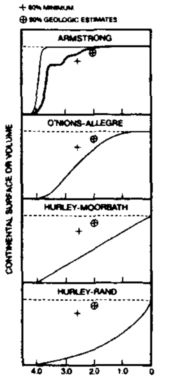
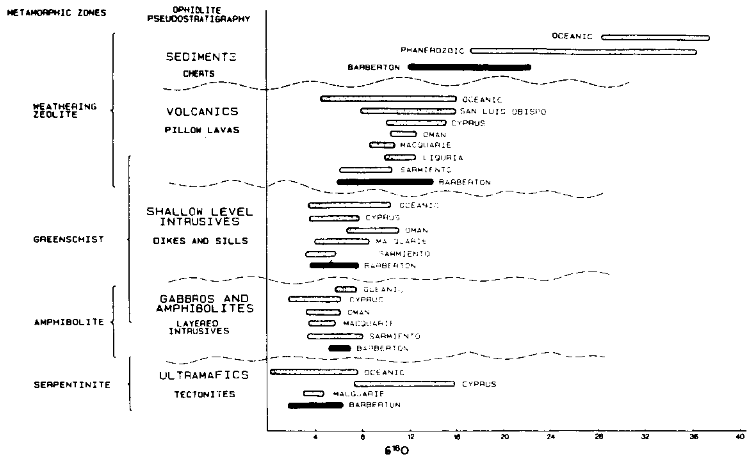


FIG 2



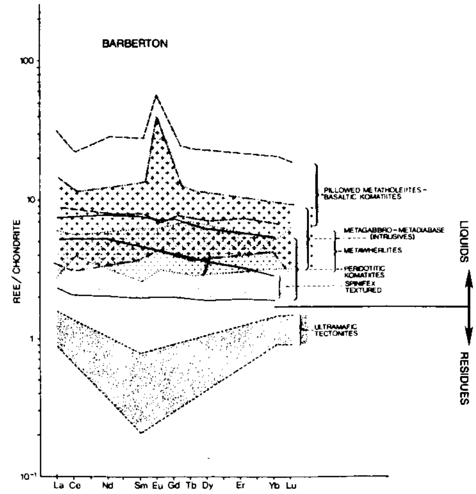
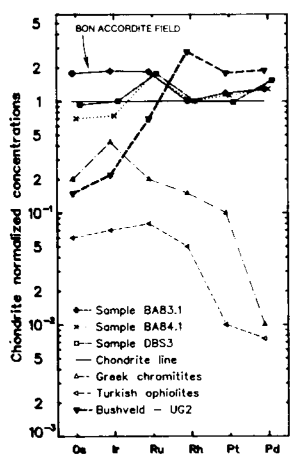


FIG 3 (a) (b)



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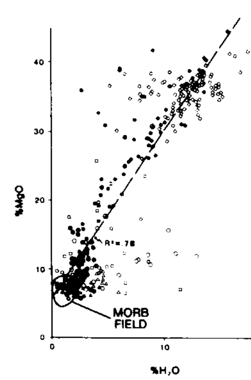

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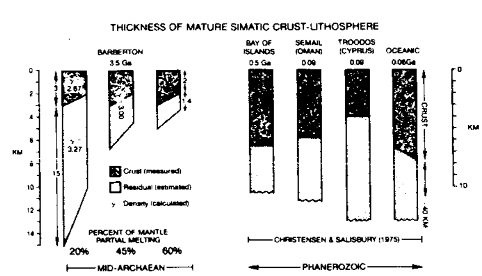

FIG 6

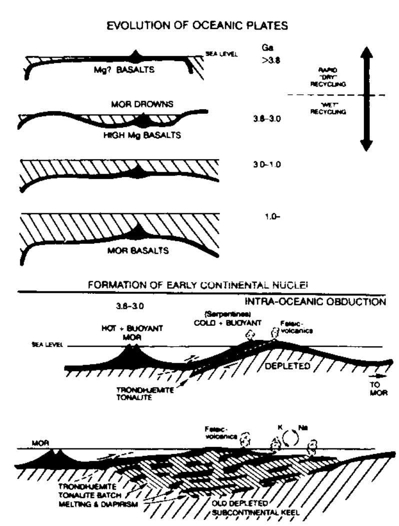

FIG 7

FIGURE CAPTIONS: (1). Archean terrains of Southern African continent with 5 located crustal sections. Data for sections I-III partly from S.A. Geodynamic Projects. The structural/chemical boundary in section III was first recognized as a 3.0 Ga or older seismic reflector by R.J. Hart (1985, in preparation). (2). Four different types of continental growth curves according to various isotopic models. My geological estimates of Archean rocks from areal distributions on a Gondwana map are also shown, and my preferred model based on this geologic data, is shown in the top model (bold line). (3). Representation of $\delta^{18}O$ (a) of the Barberton rocks (black) plotted in their restored pseudo-stratigraphic sequence compared to Phanerozoic ophiolites and oceanic crust (open symbols) (b) REE data from Barberton; this plot compares favourably with Phanerozoic ophiolites and oceanic crust. (4). PGE distribution of spinel enriched rocks derived from post 2.7 Ga upper mantle compared to those found in the 3.5 Ga residual rocks of Barberton (Bon-Accordite field), suggesting the latter were derived from (lower) mantle sources not yet entirely depleted in high-temperature platinoids (Os, lr). (5). MgO versus H_2O for spilites, greenschists, amphibolites and serpentinites from Barberton (closed symbols) and the oceanic crust (open symbols). (6). Thickness and density of Archean oceanic crust and depleted mantle lithosphere (measured and calculated from Barberton field data) compared with Phanerozoic ophiolites and oceanic lithosphere. (7). Model for the evolution of the earliest continental nuclei (granite- greenstone terrains) following the drowning of MORs circa 3.8 Ga.

REFERENCES:

Armstrong, R.L. (1981) Radiogenic isotopes: the case for crustal recycling on a near-steady-state no-continental-growth Earth Phil. Trans. Roy. Soc. Lond., A301, p. 443-472; (1968) Rev. Geophys. 6, p. 175-199.

Barker, F., Arth, J.G., Hudson, T. (1981) Tonalites in crustal evolution. Phil. Trans. Roy. Soc. Lond., A301, p. 293-303.

Campbell, I.H., and Taylor, S.R. (1983) No water, no granites - no oceans, no continents. Geophys. Res. Lett., 10, p. 1061-1064.

de Wit, M.J., Hart, R. and Hart, R. (1985) The Jamestown ophiolite complex, Barberton Mountain Belt: a reconaissance study of a composite section through 3.5 Ga simatic lithosphere (under review).

Jordan, T.H. (1981) Continents as a chemical boundary layer. Phil. Trans. Roy. Soc. Lond., A301, p. 359-373.

McGregor, V.R. (1979) Archean gray gneisses and the origin of the continental crust: evidence from the Godthab region, West Greenland. In Trondjhemites, dacites and related rocks (ed. F. Barker) Elsevier, Amsterdam, p. 133-147.

Pollack, H.N. and Sprague, D.R. (1981) Evolution of the Earth's heat loss mechanism. IASPEI London, Canada, July, 1981, abstract.

Tredoux, M., de Wit, M.J., Hart, R., Armstrong, R., Sellschop, J.P.E., (1985) PGE in the 3.6 Bon Accord Ni-Fe-Co-Cr occurrence, Barberton, South Africa: implications for crust-mantle-core segregation. 4th Intern. Platinum Symposium, Toronto, August, 1985, abstract.

NEW PERSPECTIVES ON IMAGING RADARS; J.P. Ford, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

Active remote sensing with imaging radar has been used in Earth exploration and resource evaluation for more than two decades. Radar images are formed by transmitting pulses of electromagnetic energy from a moving platform in a direction normal to the velocity vector. The radar backscatter contains a record of the spatial relations and the intensity of all points in the image swath. The strength of the backscatter is influenced by surface characteristics such as slope, small-scale roughness, and moisture content and by radar system characteristics such as the illumination geometry, polarization and wavelength of the signal. Understanding the relations between these characteristics is a major part of radar image analysis.

Airborne imaging radar systems have been operated at different wavelengths and polarizations experimentally since the late 1950's. The use of airborne radar images for Earth science applications began in the early 1960's. Airborne radar surveys are advantageous where timely detection of terrain features is required, particularly in regions where cloud cover restricts the use of other types of remote sensors. However, airborne radar systems are limited by constraints of illumination geometry and platform instability. Images characteristically have a large range of incidence angles across a relatively narrow swath. Mosaics of adjacent swaths must be prepared in order to cover large areas.

Spaceborne imaging radar began in 1978 with the launch of Seasat. The first Shuttle Imaging Radar experiment (SIR-A) followed in 1981. Each of the radar systems was operated at the same single frequency and polarization, with a fixed illumination geometry. The images acquired from these experiments cover wide swaths with a small range of incidence angles. In addition, the spaceborne platforms have been found to be very stable.

At the low incidence angle used on the Seasat imaging radar (23 deg.) the radar backscatter is very sensitive to topography. In areas of gentle slope the Seasat images show high sensitivity to subtle changes of relief. Seasat radar images of ocean surfaces allowed the measurement of surface wave patterns and mapping of ocean surface features such as eddies, current boundaries, etc. At the higher incidence angle used with SIR-A (50 deg.) the radar backscatter is dominated by small-scale surface roughness effects. In addition, the SIR-A incidence angle enabled penetration and subsurface mapping in hyperarid environments. Research results suggested that the backscatter characteristics of different natural surfaces could be used to discriminate different types of terrain.

SIR-B was launched in 1984 as a continuing step in an evolving NASA program to use spaceborne imaging radar techniques for earth and planetary exploration. Quantifying the backscatter vs. incidence angle for various surfaces was the purpose of the SIR-B experiment. Mechanical tilting of the antenna provided the ability to obtain multiple incidence coverage on successive days of the SIR-B mission. SIR-B was equipped with a digital data handling capability. Multiple incidence coverage of mountainous regions, tropical terrain, and vegetated lowlands was obtained from space for the first time. This enables investigators to study the relations between radar backscatter and incidence angle quantitatively through a range of different terrain types and surface covers. Stereo measurements that were made from multiple incidence coverages have provided a basis for topographic mapping from radar that is comparable in accuracy to existing photogrammetric techniques. This offers the potential for mapping the morphology of earth and planetary surfaces from stereo radar.

SIR-B investigations currently include studies in the areas of geology and cartography, hydrology, vegetation and oceanography. Problems that developed during the mission significantly limited the scope of the investigations. Therefore, SIR-B has been scheduled for reflight in mid-1987, possibly in a polar orbit. The polar orbit will allow radar images to be collected for the first time at high latitudes, notably in Antarctica.

The next step in this evolutionary radar program is SIR-C, which will add a multifrequency and multipolarization capability. The SIR-C radar systems will include numerous low power solid state transmitters distributed across the antenna aperture. The distributed radar will allow electronic beam steering in the range direction. Thus, it will be possible to obtain multiple incidence angle data without tilting the antenna. Present plans are for the SIR-C mission to be flown in polar orbit at different seasons in 1989 and 1990. SIR-C will be designed so that with minimum modification it can be flown on the Earth Observing System (Eos) polar platform in the mid-1990's. Other polar orbiting imaging radar systems planned for the 1990's include the European Space Agency ERS-1, Canadian Radarsat, and Japanese JERS-1. In addition, an imaging radar will orbit the planet Venus on the Magellan spacecraft in 1988 with the objective of mapping the Venusian surface at a resolution of about 150 meters.

IMAGING SPECTROMETRY, Alexander F. H. Goetz, University of Colorado/ Jet Propulsion Laboratory

Imaging of the earth's surface is used by geologists in two ways. The primary interest has been in the interpretation of morphological features and the derivative structural information. For this application, spatial resolutions of one meter or better are desired and obtainable with aerial photography. Images from orbit with poorer resolution, but with orders of magnitude more areal coverage, have been used effectively for regional analysis.

The other, less conventional segment of the community, makes use of multispectral images to extract compositional information which cannot be acquired by other remote means. The tools for multispectral remote sensing are getting better and the wavelength coverage expanding. A new concept, imaging spectrometry, seeks to acquire reflectance spectra of sufficient wavelength resolution to make direct identification of mineralogy possible.

The Airborne Imaging Spectrometer (AIS) is operational and acquiring data, albeit in 300 m swaths. The next step is to an instrument that will acquire data in 224 spectral bands simultaneously in the 0.4-2.4μm region over an 11 km swath. The first spaceborne instrument will be the Shuttle Imaging Spectrometer Experiment (SISEX), and a derivative of SISEX, the High Resolution Imaging Spectrometer (HIRIS), is being designed for the Earth Observing System (EOS) on Space Platform. The era of remote laboratory-like spectroscopy on an image pixel by pixel basis is at hand.

THE MANTLE: POTENTIAL FIELD CONSIDERATIONS

Bradford H. Hager, Seismological Laboratory, California Institute of Technology, Pasadena, CA. 91125

The accurate determination by satellite geodesy of the long-wavelength variations in geoid height and the development of the concepts of plate tectonics occurred at about the same time and led to an apparent paradox. High density subducted slabs in the upper mantle are associated with geoid highs at wavelengths of 4,000 to 10,000 km, while volcanic hot spots, presumably associated with hot, low density mantle material, are also associated with geoid highs at wavelengths of 20,000 km and less. It has been difficult to understand how both hot and cold mantle could be associated with geoid highs, so the link between mantle dynamics and the geoid has been obscure.

This apparent paradox can be resolved by taking into account the fact that over geologic time, the mantle responds to the stresses generated by internal density contrasts by slow, creeping flow. This flow results in dynamically maintained topography at the earth's surface (midocean ridges and deep sea trenches are two familiar examples), at the core-mantle boundary, and at any interior chemical boundaries that might exist. The mass anomalies resulting from this dynamically generated topography have a major effect on the geoid of opposite sign to that of the driving density contrasts and can be large enough to change the sign of the resulting geoid anomaly. For a given distribution of internal density contrasts, the surface topography and geoid anomalies depend strongly on the variation of viscosity with depth, the presence or absence of internal chemical discontinuities and the wavelength and depth of the density contrasts. [1] In particular, density contrasts near a boundary are nearly compensated and have little effect on the geoid.

At wavelengths greater than 4,000 km, surface topography is dominated by the distribution of isostatically compensated continents and oceans and by midocean ridges. These features, generated by near-surface density contrasts, have a very small geoid signature at long wavelengths, but they obscure the dynamic topography generated by density contrasts deep within the mantle.

These deep seated density contrasts can now be inferred directly using seismic tomography. [2-6] The boundary deformation caused by these density contrasts, while difficult to observe directly, can be calculated using fluid dynamical models of flow in the mantle. It is possible to account for 90% of the variance of the observed long wavelength geoid using the density contrasts inferred from body wave tomography of the lower mantle, [7] surface wave tomography of the upper mantle, and a thermal model of subducted slabs in the upper mantle, [8] if the accompanying dynamically maintained surface deformations are also included. The most successful mantle flow model calculated to date has mantle-wide flow and a viscosity increasing by a factor of 300 from the asthenosphere to the lower mantle.

Body wave tomography reveals hot material in the lower mantle beneath hot spot provinces at the surface, indicating at least thermal coupling between the upper and lower mantles. [7] The regions of hot lower mantle are those shielded from cooling by subduction during the past hundred M Yr. [9,10] At very long wavelengths, the effects of surface deformation induced by this hot lower mantle material, which include the relative uplift of Africa and the Western Pacific, dominate, resulting in geoid highs there. At shorter wavelengths, the effects of density contrasts in the upper mantle dominate. The increase in viscosity with depth results in less deformation of the upper surface from intermediate wavelength loads in the upper mantle, leading to geoid highs over subducted slabs.

POTENTIAL FIELD
Hager, B. H.

By combining dynamic models of the geoid with results from seismic tomography, it is possible to constrain the variations of density and temperature associated with variations in seismic velocity and to improve our understanding of mantle dynamics. Further progress in this field requires more accurate measurements of geoid height variation such as will be provided by GRM, higher resolution seismic studies, global determinations of dynamic topography, and more powerful computers, which will allow us to address the difficult problem of three-dimensional flow in a spherical earth with realistic rheology.

1. Richards, M. A., and Hager, B. H. (1984), *J. Geophys. Res., 89,* p. 5987-6902.
2. Dziewonski, A. M. (1984), *J. Geophys. Res., 89,* p. 5929-5952.
3. Clayton, R. W., and Comer, R. P. (1985), *J. Geophys. Res.*, submitted.
4. Woodhouse, J., and Dziewonski, A. M. (1984), *J. Geophys. Res., 89,* p. 5953-5986.
5. Nataf, H.-C., Nakanishi, I., and Anderson, D. L. (1984), *Geophys. Res. Lett., 11,* p. 109-112.
6. Tanimoto, T. (1985), *J. Geophys. Res.,* in press.
7. Hager, B. H., Clayton, R. W., Richards, M. A., Comer, R. P., and Dziewonski, A. M. (1985), *Nature, 313,* p. 541-545.
8. Hager, B. H. (1984), *J. Geophys. Res., 89,* p. 6003-6015.
9. Anderson, D. L. (1982), *Nature, 297,* p. 391-393.
10. Chase, C. G. and Sprowl, D. R. (1983), *Earth Planet. Sci. Lett., 62,* p. 314-320.

NASA PROGRAMS IN GEOLOGY; Peter J. Mouginis-Mark, Acting Geology Program Manager, NASA Headquarters, Washington, DC 20546

Individual speakers within this special session of The Earth As A Planet address the major advances in air- and space-borne instrumentation that are taking place within NASA's Terrestrial Geology Program. Such instruments should not be viewed simply as new pieces of hardware, but rather as new methods by which geological investigations can be conducted on a regional to global scale.

Major objectives within NASA's Geology Program cover a broad range of fields, from the interpretation of the process by which plate tectonics has operated to assemble and modify the continents over much of the Earth's history, to the investigation of the Quaternary record of climatic change that is preserved in the surficial rocks, and the study of transient events such as hurricane-induced coastal erosion/deposition or volcanic eruptions. Orbital radar systems (Seasat, SIR-A, SIR-B) and airborne instruments (AIS, TMS, TIMS and multifrequency/multipolarization radars) point toward an exciting revolution in the manner that earth scientists can study these phenomena, and represent evolutionary steps focused towards the Space Station Era in the mid-1990's.

Currently scheduled flights of polar orbiting radars (SIR-B' in March 1987; SIR-C in mid-1989 and early 1990) and the Shuttle Imaging Spectrometer Experiment (SISEX; 1991) offer the opportunity to conduct studies such as the mapping of considerable portions of Antarctica, investigate the paleohydrology of the hyper-arid regions of the world, and perform stratigraphic investigations of sedimentary basins worldwide. These missions are likely to be complemented by a potential fields mission (the Geopotential Research Mission, a possible FY '88 new-start). Also in the conceptual stage is an altimeter experiment, to be flown on the Space Shuttle, that would produce a global topographic data set of value to a broad range of geophysical, geomorphic and structural investigations. These experiments are being planned not only for their contributions to such diverse fields as geology, hydrology, ecology and oceanography, but also they are intended to prepare the earth sciences community for the wealth of global information to be returned in the mid-1990's by polar orbiting satellites which will form the Earth Observing System (EOS) component of the Space Station Complex.

The geological community is urged to rise to the challenge provided by these new sensors and to participate in the global study of our own planet.

Thermal Evolution of the Earth

Frank M. Richter
Department of the Geophysical Sciences
University of Chicago

Kelvin's model for the thermal evolution of the Earth (1863), whose stated goal was "to estimate from the general increase of temperature in the Earth downwards, the date of first establishment of that consistentior status which is the initial date of all geologic history", is a classic example of an approach that has as its point of departure a conception of the Earth as a planet. The Earth is represented in its simplest form: a sphere cooling by conduction from an initially uniform hot state. That the exercise failed and estimated an age almost two orders of magnitude smaller than what it really is has been the source of many moral homilies about science and scientists, yet the mode of discourse that it introduced remains central to many contemporary discussions of the Earth, including thermal evolution that continues as intellectually challenging today as it was in Kelvin's time.

Once it was realized that the age of the Earth was at least several billion years, Kelvin's original calculation posed a dilemma: How to reconcile the present thermal structure with this great age. Based on conduction alone, the Earth should be much cooler, or more precisely, have a lower heat flow than what is observed. The discovery of radioactivity and radiogenic heat production in the Earth helped reduce the discrepancy between prediction and observation, but radiogenic heat alone is demonstrably inadequate to account for the present thermal state and associated heat flow. The other key process that has to be included is thermal convection, which plays a powerful role in allowing the Earth to support its present heat flow by exploiting its entire internal heat as opposed to simply that of a thin conductive boundary layer near the surface. By including a reasonable amount of radiogenic heat production and secular cooling at all depths it is not difficult to arrive at a thermal evolution that reconciles the present thermal state of the Earth with its great age (McKenzie and Weiss, 1975; Richter, 1984).

But, as is so often the case, as one puzzle is resolved a new one arises in its place. And so it is when one looks at the predictions that thermal evolution models make for the thermal structure of the Earth during the Archean, about 3 billion years ago. They invariably predict a much higher rate of heat loss and an interior hotter by at least several hundred degrees than that of today. Under these circumstances a rheological continental lithosphere (that is, a lithosphere whose thickness depends on its temperature via viscosity, which decreases with increasing temperature) would be very thin, several 10's of km compared to about 150 km today. The associated geothermal gradient is such that widespread melting of the lithosphere and continental crust would seem inevitable. Yet numerous Archean terrains have survived and indeed many different geological observations suggest that their thermal structure and lithospheric thickness during the Archean was not appreciably different than what is typical today. The contemporary puzzle then is to explain why the Archean lithosphere (or at least those parts that have survived) was no different from todays despite the higher interior temperature of the Earth during the Archean.

One possible way out is to assume that the Archean lithosphere's thickness was relatively insensitive to temperature, controlled instead by some other property such as chemical differences between it and "normal" mantle. Jordan (1978, 1981) has argued for this on the basis of seismic travel time delays and analysis of mantle nodules. Davies (1979) and Richter (1985) discuss the thermal consequences of such a "chemical" lithosphere, and it can, almost by definition, produce the desired Archean geothermal gradient similar to that of today.

The need to appeal to something other than a simple rheological lithosphere to account for the inferred properties, past and present, of the Archean lithosphere serves as a reminder that we do not yet fully understand the continental lithosphere and the properties and mechanisms that determine its thickness. A better definition of the continental lithosphere (lithosphere that acts as a conductive lid over the convective interior as opposed to participating in the convective regime as does the oceanic lithosphere) is most sensibly sought through terrestrial data, yet its importance may well be greatest when applied to the other inner planets which not having the plate tectonic style of heat loss will have their thermal evolution controlled to a very large extent by the response of their lithospheres to the thermal state of their interiors.

References

G. F. Davies, Thickness and thermal history of continental crust and root zones, Earth Planet. Sci. Lett., 44, 231-238, 1979.

T. H. Jordan, Composition and development of the continental tectosphere, Nature, 274, 544-548, 1978.

T. H. Jordan, Continents as a chemical boundary layer, Philos. Trans. R. Soc. London, Ser. A 301, 359-373, 1981.

Kelvin, William Thomson, First Baron, On the secular cooling of the Earth, Phil. Mag. Ser. 4, 25, 1-14, 1863.

D. P. McKenzie and N. O. Weiss, Speculations on the thermal and tectonic history of the Earth, Geophys. J. R. Astron. Soc., 42, 131-174, 1975.

F. M. Richter, Regionalized models for the thermal evolution of the Earth, Earth Planet. Sci. Lett., 68, 471-484, 1984.

F. M. Richter, Models for the Archean thermal regime, Earth Planet. Sci. Lett., 73, 350-360, 1980.

THE MOON AS A PLANET; H.H. Schmitt

Consultant, P.O. Box 8261, Albuquerque, NM 87198

The interpretive evolution of the Moon as a planet can be divided now into seven major stages beginning sometime near the end of the formation of the solar system(1). These stages and their approximate durations in time are as follows:

1. The Beginning - 4.6 billion years ago.
2. The Melted Shell - 4.6-4.4 billion years ago.
3. The Cratered Highlands - 4.4-4.1 billion years ago.
4. The Large Basins - 4.1-3.9 billion years ago.
5. The Light-colored Plains - 3.9-3.8 billion years ago.
6. The Basaltic Maria - 3.8-3.0(?) billion years ago.
7. The Quiet Crust - 3.0(?) billion years ago to the present.

The Apollo and Luna explorations that permit us to study these stages of evolution each have contributed in progressive and significant ways. Through them we now can look with new insight into the early differentiation of the Earth, the nature of the Earth's protocrust, the influence of the formation of large impact basins in that crust, the effects of early partial melting of the protomantle, the evolution of life and possibly the earliest stages of the breakup of the protocrust into continents and ocean basins.

The significance of the 3 billion year age for the end of the highly active phase of lunar evolution cannot be over-emphasized. The fact that major changes ceased on the Moon about 3 billion years ago means that most of what we have learned from the Moon flights is about the first one and one-half billion years of the early history of a planet similar in major ways to our own. That 1.5 billion years of early history has been largely obscured in the Earth's crust by 3 billion years of formation and destruction of continents, mountain building, vulcanism, water and wind erosion and organic activity. Thus, the Moon gives a view into our own past. We could have hardly asked for more.

The study of the Moon shows us many things that may have been happening on Earth and Mars before and during the separation of the oceans, the atmosphere and the continents. The early periods of lunar history must have been paralleled on Earth with their effects modified by the presence of the Earth's greater gravitational forces, by an early hot fluidsphere, by early weathering and biogenetic activity and by the disruption of the Earth's crust due to sustained internal convection.

With this new insight from the Moon, we now have reasonable explanations for many of the puzzling features geologists have long observed in the oldest rocks on Earth. For example, very large, titanium-bearing bodies of calcium and aluminum-rich silicate rock (anorthosites) are probably the greatly modified relics of the Earth's first crust. Very large masses of layered basaltic rock (such as in southern Africa), rich in platinum, chromium and other important metals, are probably the massive remainders of the Earth's "maria".

Finally, the geochemical heterogenity of the crust of the Moon caused by the formation of large basins and the extrusion of mare basalts strongly suggests a similar origin for the ancient and persistent geochemical provinces in the continents of the Earth.

Possibly most important of all insights are our new ideas for explaining the development of life on Earth. The extraordinary intensity of the impact history of the first 500 million years of lunar evolution strongly suggests a similar history for the Earth and Mars. The presence of clay minerals and the continuous supply of energy and complex hydrocarbon molecules from debris falling into the Earth's hot atmosphere during this period may have been the basis for the creation of the first very complex organic chemicals which could "evolve" and "reproduce" either on clay templates(2) or as independent complex organic compounds. The 3.5 billion-year-old bacterial fossils recently discovered in Australia and Africa(3,4) at least tend to support this thesis of very early organic evolution and add major excitement to the future paleontological exploration of Mars. On Mars, this universal process of "terrestrial" biological evolution may have been arrested in various phases as the Mars environment changed from one similar to that of Earth to one similar to that of the Moon.

References:

(1) Schmitt, H.H. (1975) Space Science Reviews, 18, p.259-279.

(2) Cairns-Smith, A.G. (1985) Scientific American, 252, No. 6, p.90-100.

(3) Schopf, J.W., editor, (1983) Earth's Earliest Biosphere, Princeton University Press, p.214-238

(4) Walsh, M.M. and Lowe, D.R. (1985) Nature, 314, p.530-532

GEOMORPHOLOGY FROM SPACE: A GLOBAL OVERVIEW OF REGIONAL LANDFORMS; Nicholas M. Short, Geophysics Branch, Code 622, Goddard Space Flight Center, Greenbelt, MD 20771.

The NASA and Soviet Extraterrestrial Exploration programs focused attention of the geosciences communities on the evolution of planetary surfaces by a variety of processes, many of which also operate on the Earth's exterior. Comparative planetology developed as an approach to analysis mainly to the genesis of geomorphic features observed on other planets, leading to greater insights into the formation and variability of their terrestrial counterparts. Imaging sensors sent past or around the planets have fostered an intense and systematic mapping of their surfaces at scales considered too small to be useful on Earth except to summarize regional syntheses, yet the resulting maps have led to an appreciation of the global history of these planets as unitary bodies rather than as the isolated segments usually treated in Earth studies. Ironically, there is no modern version of "The Geology of the Earth" (as a planet) whereas books on the geology of the Moon and Mars as a whole have emerged from space technology.

The advent of Landsat and other earth-observing satellites in the 1970's offered an opportunity to examine the terrestrial land surfaces at scales and resolutions similar to those used successfully on the other planets. But, for a decade attention was directed towards practical applications, mostly in resources prospecting, of the wealth of imagery rather than on more fundamental scientific questions. A notable exception arose from use of Landsat mosaics as an information source in synthesizing the tectonics of large regions of Asia and orogenic belts elsewhere. Now, NASA programs are diversifying to include investigations of the morphotectonics of the continental crust along with other aspects of regional landforms analysis in a manner analogous to the well-established methods of planetary exploration.

Three achievements in these growing studies will be reviewed. First, a NASA book having the same title as this paper is scheduled for publication in 1986. Second, a Workshop on Global Megageomorphology held in January 1985 produced specific proposals for future research. Third, the author will report on the First International Conference on Geomorphology conducted in September 1985 at Manchester, England, where other signs of renewed interest in regional-scale geomorphology emerged.

PLANETARY DEGASSING: K.K. Turekian, Dept. of Geology and Geophysics, Yale University, Box 6666, New Haven, CT 06511

The growth of radiogenic ^{40}Ar in the atmosphere is a function of the potassium content of the Earth, its age and the pattern of release of non-reactive gasses from the Earth's interior. This can be simply represented by:

$$\frac{d\,A(t)}{dt} = \lambda\, K_o e^{-\lambda t} - \alpha e^{-\beta t}\, A(t)$$

where: A(t) is the radiogenic ^{40}Ar in the solid Earth as a function ot time; K_o is the amount of ^{40}K 4.55×10^9 years ago that will decay to ^{40}Ar. This is related to the total amount of ^{40}K through the branching ratio; t is the time elapsed since the beginning of the Earth; λ is the decay constant of ^{40}K; α and β are constants controlling the rate of degassing as a function of time. The equation is naive in that it contains no detailed information on mechanisms and ignores the structure of the Earth's interior. The use of similar equations has been made by Allegre's group in Paris [1].

The following parameters are used in the solution of this equation by numerical integration: bulk (whole) Earth K = 300 ppm; atmospheric $^{40}Ar = 9.85 \times 10^{41}$ atoms; age of Earth = 4.55×10^9 years; mass of Earth = 5.97×10^{27} grams; $K_o = 3.96 \times 10^{42}$ atoms; $\lambda = 5.30 \times 10^{-10} y^{-1}$.

The solutions in terms of $A(t)/K_o$ are given for a number of combinations of α and β. The choice of acceptable solutions is set by the present-day value for A/K_o of 0.66.

One limit is set by $\beta = 0$. The value of α is then $1.05 \times 10^{-11} y^{-1}$. This is the simple degassing model used by me earlier [2]. An alternative solution yielding approximately the same present-day A/K_o value has $\alpha = 10^{-9} y^{-1}$ and $\beta = 10^{-9} y^{-1}$. Each of these two solutions yields a value for the present-day ^{40}Ar degassing rate. Each predicted degassing rate can be compared to that determined from rare gas measurements in MORB glass and the estimated ^3He flux from sea water measurements. For $\alpha = 1.05 \times 10^{-11} y^{-1}$, $\beta = 0$, the predicted degassing present-day rate is 2.75×10^{32} atoms $^{40}Ar\ y^{-1}$. For $\alpha = 10^{-9} y^{-1}$, $\beta = 10^{-9} y^{-1}$ the predicted present-day degassing rate is 2.8×10^{31} atoms $^{40}Ar\ y^{-1}$. Hydrothermal vent degassing determined as described yields a value of 2.7×10^{32} atoms $^{40}Ar\ y^{-1}$, indicating that a virtually constant degassing rate constant over time for ^{40}Ar is not unrealistic.

When these results are applied to other gases, the following are the consequences:

1. Only 2% of non-radiogenic ^{36}Ar in the atmosphere can be supplied by degassing from the interior over time.

2. If the carbonaceous chondrite $H/^{36}Ar$ ratio of 6.14×10^8 is used and this is the carrier of the degassing component, 33% of the present hydrosphere could be supplied by continuous degassing if water behaved like argon. If hydrogen has been lost from the atmosphere, the $H/^{36}Ar$ ratio is less than that for carbonaceous chondrites, or degassing is less efficient for reactive gases than argon, then less than this value has been derived by continuous degassing.

PLANETARY DEGASSING

K.K. Turekian

Obviously the Earth's atmosphere is derived from two different processes: (1) an initial veneer, and (2) a component within the Earth degassing on a slower time scale. If we assume no major modification of the veneer volatiles after the formation of the initial atmosphere and hydrosphere occurred, then the following properties of the veneer must be accepted: it is low in I (^{129}Xe constraint); it has a different Xe, Kr and Ne isotopic composition from carbonaceous chondrites; it is considerably lower in H and C relative to ^{36}Ar compared to C-1 carbonaceous chondrites. This is not incompatible with a primitive gaseous veneer derived from the surrounding solar nebula as envisaged by Hayashi and his co-workers at Kyoto [3]. The consequences of this model for early Earth history have been discussed by this group. Other two-process models of the formation of the atmosphere and hydrosphere can also be conceived of by imaginative degassers from all over the world.

[1] Staudacher, Th. and Allegre, C.J. (1982) Earth Planet. Sci. Letters, v. 60, p. 389-406.
[2] Turekian, K.K. (1959) Geochim. Cosmochim. Acta, v. 17, p. 37-43.
[3] Hayashi, C., Nakazawa, K. and Mizuno, H. (1979) Earth Planet. Sci. Letters, v. 43, p. 22-28.

MEGAGEOMORPHOLOGY: A NEW ORBITAL PERSPECTIVE

G. L. Wells, Photography and Television Technology Division, Code JL,
NASA Johnson Space Center, Houston, Texas 77058

There are two qualities that separate the pursuit of mègageomorphological investigations from routine geomorphological research. The first and more common characteristic is that megageomorphology studies the large-scale integration of classical landform aspects that taken together reveal the operation of a regional process. For example, the recent ability to morphometrically analyze each individual sand dune within an entire desert basin using Landsat images has led to new theories of dune development in response to regional wind regimes, when the photo-analyses have been conducted in relation to field studies of individual sand dunes and compared to wind frequency data recorded by adjacent meteorological stations. The second and more exciting characteristic is that megageomorphology explores processes occurring on scales too large to be fully appreciated by traditional methods of geomorphological inquiry. To take parallel examples, the basin-to-basin sand flow shifting material amongst the many Saharan basins and the transport dynamics of Saharan dust storms whose products are deposited in the abyssal depths of the Atlantic are two geomorphological systems about which little would be known without the benefit of orbital Earth-imaging instruments.

Perhaps the best way to judge the status of megageomorphology in the study of the Earth as a planet is to recall a couple of its past contributions and to re-examine the conclusions of these investigations in light of new field evidence and recent innovations in orbital reconnaissance techniques. Two pivotal works which I would not hesitate to label modern geological classics are the tectonic mechanism by which Eurasia accommodates the collision with India as developed by Peter Molnar and Paul Tappannier and the regional studies of global sand seas inspired by Ed McKee and conducted by Carol Breed, Stephen Fryberger, Jack McCauley and others. Both investigations were begun in the mid-1970's, made extensive use of Landsat images and found unique means to incorporate field data into the regional analyses of orbital imagery.

THE COLLISION BETWEEN INDIA AND EURASIA.

During the past twenty years, a driving force in the study of plate tectonics has been the question of how Eurasia has responded to the Eocene impact with India and subsequent displacement of at least 1500 kilometers of continental crust. Molnar and Tappannier (1,2,3,4,5) provided the first comprehensive account of Cenozoic Eurasian tectonics originating from the Indian collision. Their study began with the assembly of panregional Landsat mosaics that allowed them to identify vast fault systems crossing central Asia, including the Altyn Tagh, Kunlun, Kang Ting, Karakoram and Talasso Fergana. The locations of earthquake epicenters and their fault plane solutions were plotted in relation to the fault systems. Though in some cases derived from poorly-constrained seismic events, these relative movements were combined with detailed inspection of portions of the Landsat fault traces to provide evidence that the faults displayed strike-slip characteristics. The discovery of apparent left-lateral strike-slip faults crossing western China led to a model of Eurasian tectonics where India acts as a rigid wedge driving northward, and the Tarim Basin serves as a stable, immobile craton. The continental collision forces the eastward escape of the Chinese block along the left-lateral strike-slip faults. Offsets of more than 1000 kilometers are inferred, but not a single example of recent offsets could be identified from the Landsat images. Molnar and Tappannier concluded that their hypothesis 'would be fatally wounded if it could be shown that the displacement along the major faults amounts to only a few kilometers or at most a few tens of kilometers over the past 40 million years.'(3).

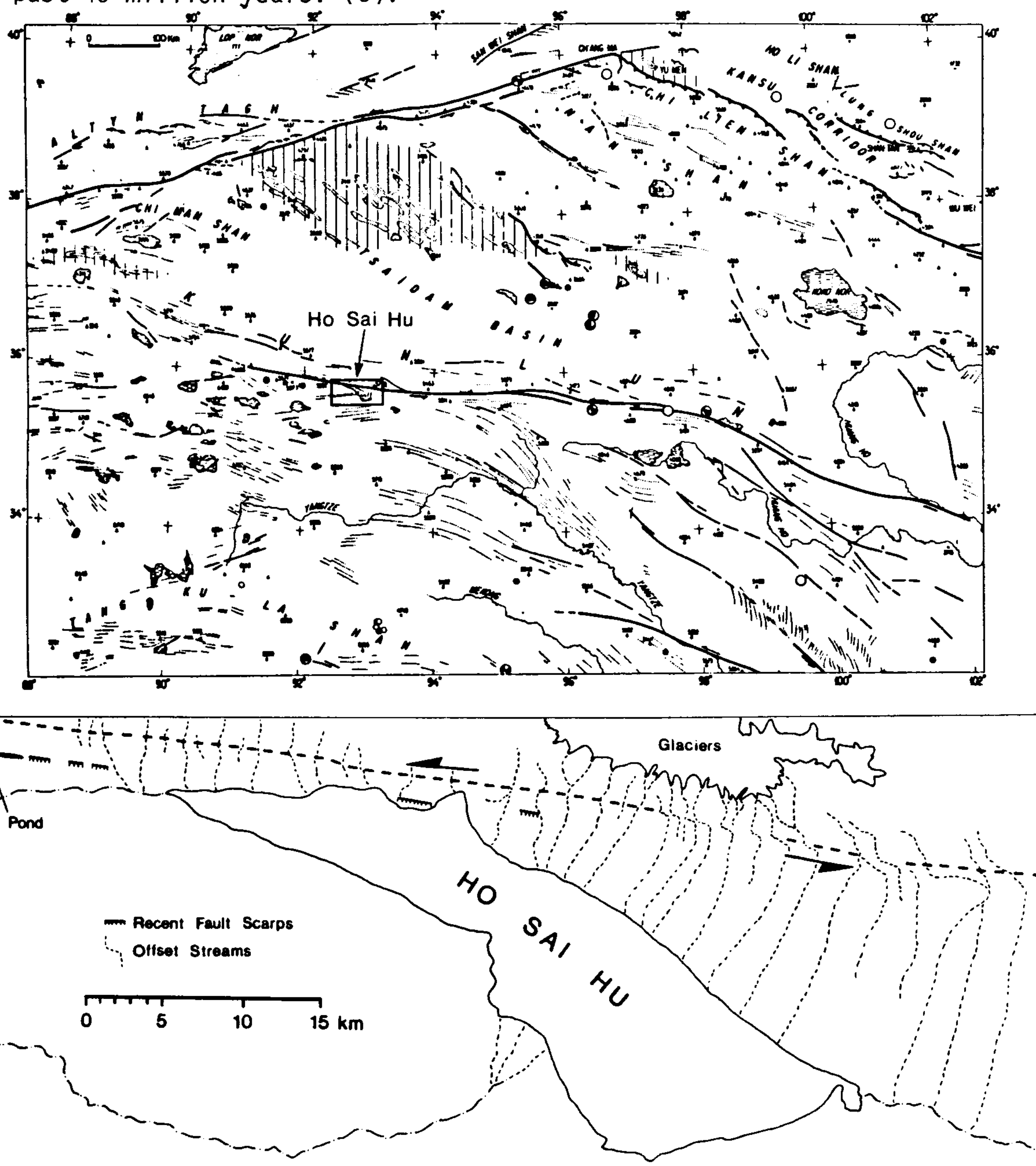

Figure 1. The seismotectonic map (top) of Tibet, Tsaidam Basin and the Kunlun and Nan Shan mountain belts was derived from Landsat image mosaics prepared by Molnar and Tappannier (4). The inferred strike-slip movements were determined by the tectonic context and proximity to seismic events demonstrating left-lateral motions. A map of the Kunlun Fault at Ho Sai Hu (bottom) was produced from a Large Format Camera photograph (41G-LFC-0818). Stream offsets of more than 1 km along post-glacial channels indicate a rate of displacement of 5-10 $cm \cdot yr^{-1}$ (6).

Photographs with 10-meter spatial resolution obtained by the Large Format Camera (LFC) over Tibet during the STS-41G mission in October 1984 vividly display a series of recent left-lateral offsets along the Kunlun Fault (Figure 1.) in an area where the estimated rate of displacement yields 5 to 10 centimeters per year (6). The summer of 1985 Chinese-British Joint Geotraverse reported left-lateral offsets along the Kunlun Fault amounting to more than 25 kilometers within Quaternary alluvial deposits located 120 kilometers east of the Ho Sai Hu area in the LFC frames. Moreover, stereoscopic, high-resolution LFC coverage together with STS astronaut Hasselblad and Linhof photography has permitted the discovery of additional strike-slip faults with recent offsets across the Tibetan Plateau and areas of recent uplift and dissection of Tertiary formations between intersecting strike-slip systems. Quaternary volcanoes have been found and an area revealing Paleozoic folds visible in the LFC and astronaut photographs but not detected on 80-meter resolution Landsat MSS images.

Perhaps the most startling revelation of the stereoscopic LFC photography is the obvious degree and extent of folding on the Tibetan Plateau. Based upon their analyses of Landsat imagery, Molnar and Tappannier downplayed the role of folding in Tibet (1,3,4). Much of what they label a subtle 'tectonic fabric' turns out under stereoscopic inspection to be tightly-compressed fold belts immersed in Tertiary and Quaternary alluvium. The existence of extensive folding in Tibet supports the theory that crustal shortening plays a significant part in the accommodation of the Indian collision, an idea first advanced by Dewey and Burke (7). Recent field reports from the Chinese-British Joint Geotraverse emphasize the importance of compression in the tectonic evolution of Tibet.

Ten years after Molnar and Tappannier's seminal contribution, their theory has been in part vindicated and in part amended. The tectonics of the India-Eurasia collision appear to be governed by both lateral displacement and accordion folding. New Earth-imaging techniques have again supplied the crucial evidence.

THE ORIGIN OF LONGITUDINAL SAND DUNES.

Another megageomorphological project of vast scope has been the work of McKee and Breed, et. al. (8,9,10,11) studying the distribution of sand dune types accummulating in the major sand basins of the world. Their research strategy began with the construction of Landsat mosaics for 15 sand seas. Wind frequency data from local meteorological stations was computed to derive potential sand drift and resultant directions for sand dune movement within areas of sand basins. These theoretical calculations were compared with historical field observations, such as those of McKee and Tibbets in Libya (12), and with a variety of morphometrical indices measured from Landsat images used to compare similar sand dune formations in different parts of the world. New theories were proposed accounting for the development of different sand dune types in relation to different wind regimes (10).

Of particular importance are the findings for environments where longitudinal sand dunes have formed (9). In many instances, these sand dunes occur in regions with bimodal, seasonally-oscillating winds that create dominant sand transport vectors which are between 90° to 180° out-of-phase, where the annual sand drift resultant lies parallel to the axes of the longitudinal sand dunes. This characteristic agreed well with the field studies of McKee (12). However, Tsoar (13) has recently argued that longitudinal sand dunes can evolve from transverse or barchanoid dunes, when these bedforms of unimodal sand transport move into regions with bidirectional airflow asymmetries. In Tsoar's hypothesis, the angle of the sand-moving wind vector at the point of attachment to the windward flank of a longitudinal dune creates several possible secondary flow directions for sand transport and determines the areas of local deflation and deposition. The presence of the longitudinal sand dune is seen to modify the boundary layer and to determine the paths of sand drift in relation to the regional wind regime.

Tsoar's observation can be extended and amplified by an analysis of LFC and astronaut photographs that clearly show the orientation of sand dune slipfaces across a broad region of large and smaller sand dunes. In the Namib Desert, Breed, et. al. (9) identified on Landsat images a local zone of coastal crescentic sand dunes and an interior region of massive longitudinal dunes which locally grade into star dunes. Unfortunately, sand dune slipfaces and the heights of individual dunes can rarely be determined using Landsat images. In the same region of Namibia, LFC and astronaut Hasselblad photographs allow the detection of three bedform zones of small (10-25 meter slipfaces) barchan dunes along the coastal plain, medium-sized (40 meter) crescentic dunes in the near-coast region and large (100 meter) longitudinal dunes in the interior grading into star dunes. Of major interest is the observation that virtually all of the smaller barchanoid dunes (10-25 meter slipfaces) distributed across the three zones have the same slipface orientation indicating south to north sand transport, whether located along the coast or in the interior. As the bedform types appear to change across the Namib Desert in relation to slipface height, it appears that the size of a sand dune may greatly influence the paths of sand drift across it and alter its shape.

The autodynamic character of bedform evolution in relation to regional airflow is reflected in the large and smaller sand dunes found in several active Saharan basins, where the small barchanoid dunes appear to represent relatively unimodal regional airflow, and the draa-sized, large dunes exhibit highly-complex slipface orientations created by secondary sand drift directions generated by the sand dunes themselves (e.g., in the Erg Chech and Marzuq Basin). The sand dune height necessary to achieve these secondary flow paths may bear a direct relationship to the total wind energy regime, where low-energy environments create sand dunes with autodynamic morphologies at lower slipface heights than high-energy environments where the regional airflow will persist in its imprint.

A retrospective look at the studies of Molnar and Tappannier and McKee and Breed confirms their importance to continuing Earth science research. In both instances, recent developments in orbital remote sensing have led to new ideas and discoveries concerning their original works. Judging from their past success and the nature of the new findings, the megageomorphologist needs images of the Earth having several specific characteristics. These images should be both broad in scale and rich in detail to allow entire regions to be studied with high spatial resolution. Stereoscopic images with different viewing geometries will provide necessary information about slopes, while images made with a variety of sun elevations and solar azimuths will serve to highlight subtle terrain features. The generation of such images will be a tremendous aid to our future understanding of the planet.

References:

1. Molnar P. and Tappannier P. (1975) Science 189, p. 419-426.
2. Tappannier P. and Molnar P. (1976) Nature 264, p. 319-324.
3. Molnar P. and Tappannier P. (1977) Sci. American 236, No. 4, p. 30-41.
4. Tappannier P. and Molnar P. (1977) J. Geophys. Res. 82, p. 2905-2930.
5. Tappannier P. and Molnar P. (1979) J. Geophys. Res. 84, p. 3425-3459.
6. Wells G. L., Burke K. and Francis P. W. (1985) EOS Trans. Am. Geophys. Union 66, p. 375.
7. Dewey J. F. and Burke K. C. A. (1973) Geology 81, p. 683-692.
8. McKee E. [Ed.] (1979) U. S. Geol. Survey Prof. Paper 1052, 429 p.
9. Breed C. S., Fryberger S. G., Andrew S. E., McCauley C., Lennartz F., Gebel D. and Horstman K. (1979) In U. S. Geol. Survey Prof. Paper 1052, p. 305-398.
10. Fryberger S. G. and Dean G. (1979) In U. S. Geol. Survey Prof. Paper 1052, p. 137-170.
11. Breed C. S. and Grow T. (1979) In U. S. Geol. Survey Prof. Paper 1052, p. 253-304.
12. McKee E. D. and Tibbets C. (1964) J. Sed. Petrol. 34, p. 5-17.
13. Tsoar H. (1978) Final Tech. Rep., European Research, Office U. S. Army, 171 p.

CHEMICAL GEODYNAMICS; A.Zindler[1] and S.R. Hart[2], [1]Lamont-Doherty Geological Observatory of Columbia University, Palisades, NY 10964, and [2]Dept. of Earth and Planetary Science, Massachusetts Institute of Technology, Cambridge, MA 02139

Consideration of the chemical composition of present-day mantle materials (in the form of xenoliths erupted in basalts, and tectonically exposed ultramafic massifs) precisely defines the concentrations of the lithophile refractory elements Ca, Al, Mg, Si, Sr, U and the REE in the primitive upper mantle (PUM), and inferentially, in the bulk silicate earth (BSE). The values for refractory lithophile elements in the BSE are defined as 2.47xCl chondrites, in agreement with chondrite-based earth models.

The present mantle is chemically heterogeneous both on small scales (<10m) and on very large (1000 km) scales, as deduced from isotopic studies of tectonically exposed ultramafic massifs and mantle-derived basalts. The heterogeneities in the heavy isotope tracers (Sr, Nd and Pb) are consistently interrelated in mantle materials and currently can be resolved into 4 end-member, and perhaps 1 or 2 intermediate, "components". The He isotope tracer data cannot be consistently resolved in the context of these components, and is subject to potentially serious perturbations due to ingrowth of radiogenic ^{4}He due to pre-eruptive degassing.

The mantle reservoir from which MORB is derived (DMM) is situated in the uppermost mantle, and could constitute as little as 10% of the whole mantle. The mantle below the 670 km discontinuity, is, on average, moderately depleted, and cannot be wholly of undifferentiaged BSE composition. A high U/Pb (HIMU) component and two enriched (EM I, EM II) components are required to be present in the mantle. HIMU may be either a mantle residue from which a metasomatic fluid has been extracted, or it may evolve from ancient subducted oceanic crust. EM I and EM II have isotopic signatures reminiscent of lower and upper continental crust respectively; they may indeed represent recycled crustal components, or they may be the products of intramantle metasomatism, involving CO_2 rich fluids (EM I) and H_2O-rich fluids (EM II). The mean composition of the mantle is depleted, with $^{143}Nd/^{144}Nd$ = 0.51280-0.51305. This composition may represent a mixture of DMM, HIMU, EM I, EM II, ±BSE, or it may exist as an actual prevalent mantle (PREMA) component of moderately homogeneous composition. If the latter case is true, a very sizable fraction of the mantle could be PREMA.

The U content of the BSE is well constrained to be 21 ppb. From 22% to 52% of this BSE U budget currently resides in the crust. The reduced (mantle) Urey is ~2.8, suggesting mantle convection regimes with poor thermal efficiency, or a large component of heat deriving from the core.

The geochemical data, taken in concert, does not provide unequivocal evidence for either whole or layered present day mantle convection; it can be construed as consistent with either. We can, however, preclude the existence of a primitive undifferentiated lower mantle, and consequently, a persistent unbreachable boundary to convection at 670 km for all of earth history. In conjunction with geophysical constraints, a satisfying (but not unique) compromise model might involve a laterally discontinuous and periodically unstable boundary layer at 670 km.

List of Registered Attendees

Arden Albee
MS 180-904
Jet Propulsion Laborctory
4800 Oak Grove Drive
Pasadena, CA 91109

Don L. Anderson
Seismological Laboratory
California Institute of Technology
Pasadena, CA 91125

Raymond E. Arvidson
Dept. of Earth and Planetary Science
Washington University
St. Louis, MO 63130

Lewis D. Ashwal
Lunar and Planetary Institute
3303 NASA Road One
Houston, TX 77058-4399

Samuel A. Bowring
Dept. of Earth and Planetary Science
Washington University
St. Louis, MO 63130

Robin Brett
National Center MS 959
U.S. Geological Survey
Reston, VA 22092

Kevin Burke
Lunar and Planetary Institute
3303 NASA Road One
Houston, TX 77058-4399

Philip Christensen
Dept. of Geology
Arizona State University
Tempe, AZ 85287

Cornel de Ronde
Geology Dept.
University of Toronto
Toronto, Ontario,Canada M5S 1A1

Maarten de Wit
Bernard Price Institute for Geophysical Research
University of Witwatersrand
Johannesburg 2001, South Africa

David DesMarais
Exobiology Division
MS 239-12
NASA/Ames Research Center
Moffett Field, CA 94035

Steve Dickson
Chemistry Division
Oak Ridge National Lab
P.O. Box X
Oak Ridge, TN 37830

Mary C. Eberle
1520 Cress Ct.
Boulder, CO 80302

Noel Eberz
27421 Sherlock Road
Los Altos Hills, CA 94022

R. F. Emslie
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario, Canada K1A 0E8

Eric Erslev
Dept. of Geology
Lafayette College
Easton, PA 18012

John Everett
Earth Satellite Corporation
7222 47th Street
Bethesda, MD 20015

Robert H. Filson
Dept. of Geology
Green River Community College
Auburn, WA 98002

John Ford
MS 183-501
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

Patrick Gleason
1131 N. Palmway
Lake Worth, FL 33460

Alexander F. H. Goetz
MS 183-501
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

Glen Green
Dept. Earth and Planetary Science
Washington University
St. Louis, MO 63130

Richard Grieve
Earth Physics Branch
Energy, Mines and Resources
1 Observatory Crescent
Ottawa, Ontario, Canada K1A 0Y3

John Griffin
4920 Woodland Ave.
Lincoln, NE 68516

Edward Guinness
Dept. of Earth and Planetary Science
Washington University
St. Louis, MO 63130

Brad Hager
Seismological Laboratory
California Institute of Technology
Pasadena, CA 91125

R. A. Heimlich
Dept. of Geology
Kent State University
Kent, OH 44242

Lincoln Hollister
Dept. of Geological and Geophysical Sciences
Princeton University
Princeton, NJ 08540

Travis L. Hudson
1209 Orca Street
Anchorage, AK 99501

Anne Kahle
MS 183-501
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

Nan Lindsley-Griffin
Dept. of Geology
University of Nebraska
214 Bessey Hall
Lincoln, NE 68588-0340

Baerbel Lucchitta
U.S. Geological Survey
2255 N. Gemini Drive
Flagstaff, AZ 86001

Ted Maxwell
National Air and Space Museum
Room 3102
Smithsonian Institution
Washington, DC 20560

R. H. McNutt
Dept. of Geology
McMaster University
Hamilton, ON L8S 4M1 Canada

Eldridge M. Moores
Dept. of Geology
University of California
Davis, CA 95616

Paul Morgan
Box 6030, Geology Dept.
Northern Arizona University
Flagstaff, AZ 86011

S. A. Morse
Geology Dept.
Univ. of Massachusetts
Amherst, MA 01003

Peter Mouginis-Mark
Code EE
NASA Headquarters
Washington, DC 20546

Robert O. Pepin
School of Physics and Astronomy
Room 148, Physics Building
University of Minnesota
Minneapolis, MN 55455

William C. Phinney
Code SN4
NASA Johnson Space Center
Houston, TX 77058

Mary Reagan
Dept. of Geosciences
Purdue University
West Lafayette, IN 47904

Frank Richter
Dept. of Geophysical Sciences
University of Chicago
Chicago, IL 60637

Gerald M. Ross
Dept. of Earth and Planetary Science
Washington University
St. Louis, MO 63130

Peter Salpas
Dept. of Geological Sciences
University of Tennessee
Knoxville, TN 37996

Craig Schiffries
Dept. of Geological Science
Harvard University
Cambridge, MA 02138

Lloyd Schmaltz
Dept. of Geology
Western Michigan University
Kalamazoo, MI 49001

H. H. Schmitt
Box 8261
Albuquerque, NM 87198

Denis Shaw
Dept. of Geology
McMaster University
Hamilton, Ontario, Canada

Henry F. Shaw
Dept. of Geology and Geophysics
University of Minnesota
Minneapolis, MN 55455

Steven B. Shirey
Dept. of Terrestrial Magnetism
Carnegie Institution of Washington
5241 Broad Branch Road, N.W.
Washington, DC 20015

Mohamed Sultan
Dept. Earth and Planetary Science
Washington University
St. Louis, MO 63130

S. Ross Taylor
Research School of Earth Sciences
Australian National University
Canberra, A.C.T. 2601

M. Tatsumoto
U.S. Geological Survey
MS 963
Federal Center Box 25046
U.S. Dept. of Interior
Denver, CO 80225

Lawrence A. Taylor
Dept. of Geological Sciences
University of Tennessee
Knoxville, TN 37916

Marilyn Truscott
Dept. of Geology
McMaster University
1280 Main Street West
Hamilton, Ontario, Canada L8S 4M1

Karl Turekian
Dept. of Geology and Geophysics
Yale University
210 Whitney Ave.
New Haven, CT 06520

James R. Underwood, Jr.
Dept. of Geology
Thompson Hall
Kansas State University
Manhattan, KS 66506

Kenneth J. Van Dellen
Room G-401
South Campus
Macomb County Community College
Warren, MI 48093

Jan Veizer
Dept. of Geology
University of Ottawa
Ottawa, Canada K1N 6N5

Richard J. Walker
Dept. of Earth and Space Sciences
State University of New York
Stony Brook, NY 11794

Gordon Wells
Code SP44
NASA Johnson Space Center
Houston, TX 77058

Don Wise
Dept. of Geology
University of Massachusetts
Amherst, MA 01003

E. Zen
U.S. Geological Survey
National Center MS 959
Reston, VA 22092